Available online at www.sciencedirect.com

ScienceDirect

Procedia Environmental Sciences 5 (2011) 178–183

Procedia Environmental Sciences

2010 International workshop from the International Congress on Environmental Modeling and Software (iEMSs2010)

Comparison of different urban development strategy options to the urban metabolism optimal path

Gengyuan Liu, Zhifeng Yang*, Bin Chen

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China

Abstract

An urban metabolic optimization model of energy resources consumption and airborne pollution emissions is built up in this paper, and taken as a yardstick for the efficiency of the four different scenarios measures for urban development. Sensitivity Analysis is proposed to the emergy approach in order to explain the procedure and the obtained results for the selected case study of Beijing metabolic system in the year 2006. The solution to the urban optimization problem can be obtained using the optimal control theory as an analytical tool. In this case, the theory of optimal control gives a normative answer to the question how the utilization of the resources inputs and the environment has to be chosen to maximize inter-temporal welfare. The results imply that during the investigation period, steel and iron have the most significant correlation between global environment impact and local economic development, which results from rapid construction growth favored by the local government in Beijing based on the results of the optimization and the comparison with different options of Chinese resource restructuring strategy, the following ranking of strategic options can be derived: increasing energy efficiency, implementing greenhouse gas control and air pollution treatment after the end of major infrastructure construction.

Keywords: Sensitivity analysis; Emergy evaluation; Optimal path

* Corresponding author. Tel.: +86 10 58807951; fax: +86 10 58800397.
E-mail address: zfyang@bnu.edu.cn (Zhi-Feng Yang).

1878-0296 © 2011 Published by Elsevier Open access under CC BY-NC-ND license.
doi:10.1016/j.proenv.2011.03.065

1. Introduction

The research activity today is highly diverse in different scientific disciplines and sub-disciplines, which are used to study a myriad of research problems - not only from a number of different theoretical perspectives but also with several quite different types of research methods [1, 2]. This diversity of methods implies rich opportunities for cross-validating and cross-fertilizing research procedures, findings, and theories. Each type of method, if it is well and appropriately applied, can lead to potentially valid empirical and theoretical generalizations about the investigated system.

Each type of method, considered alone, is insufficient in this respect. In order to better understand the dynamics and performance of an investigated system, it is fundamental to develop an integrated model which is able to take into account all the different aspects: energy and material flows, land use, rate of resources use, interrelations of socioeconomic and natural systems, among other parameters [3,4].

In general, the economic performance is the aspect that policy makers and managers consider with more interest, due to its links to the employment and social parameters (economic and social sustainability). However, a comprehensive evaluation cannot disregard the resource use and environmental aspects, which also helps shed light on the sustainability of the investigated sector or process by focusing on crucial factors such as energy consumption, material resource use and environmental integrity.

As a thermodynamic-based environmental accounting approach, the emergy synthesis projects local input flows to the scale of biosphere, by converting all materials, energy sources, human labor and services required directly and indirectly into emergy unit that are summed up to yield the total emergy [5-7]. The method can provide invaluable insights into the hidden environmental costs and inherent (un)sustainability of even seemingly "clean" systems. On the other hand, downstream methods are often more closely related to the immediate perceived impact on the local ecosystem, and can unveil large differences between systems with similar upstream performance. In order to complete emergy approach with a scenario analysis in the following section, an explanation of the importance and the meaning of the sensitivity analysis will be elucidated first.

2. Sensitivity analysis

Sensitivity Analysis has been applied to different dataset to point out the system behavior and policy implications in relation to different scenarios. Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model. In this study, we focus on parameter sensitivity. Parameter sensitivity is usually performed as a series of tests in which the modeler sets different parameter values to see how a change in the parameter causes a change in the dynamic behavior of the stocks. By showing how the model behavior responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation [8].

In more general terms, uncertainty and sensitivity analyses investigate the robustness of a study when the study includes some form of mathematical modelling. Sensitivity analysis can be useful to computer modellers for a range of purposes, including:

(1) supporting decision making or the development of recommendations for decision makers (e.g. testing the robustness of a result);

(2) enhancing communication from modellers to decision makers (e.g. by making recommendations more credible, understandable, compelling or persuasive);

(3) increased understanding or quantification of the system (e.g. understanding relationships between input and output variables); and

(4) model development (e.g. searching for errors in the model).

Sensitivity analysis helps to build confidence in the model by studying the uncertainties that are often associated with parameters in models. Many parameters in system dynamics models represent quantities that are very difficult, or even impossible to measure to a great deal of accuracy in the real world. Also, some parameter values change in the real world. Therefore, when building a system dynamics model, the modeler is usually at least somewhat uncertain about the parameter values he chooses and must use estimates. Sensitivity analysis allows him to determine what level of accuracy is necessary for a parameter to make the model sufficiently useful and valid. If the tests reveal that the model is insensitive, then it may be possible to use an estimate rather than a value with greater precision. Sensitivity analysis can also indicate which parameter values are reasonable to use in the model. If the model behaves as expected from real world observations, it gives some indication that the parameter values reflect, at least in part, the “real world”.

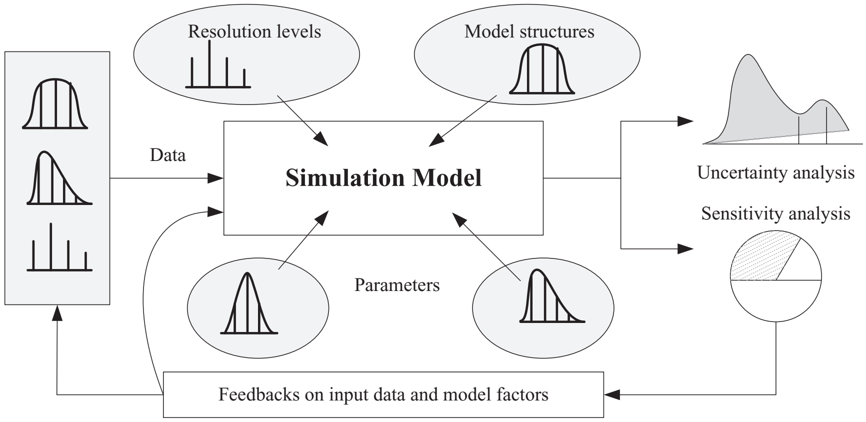

Fig. 1 Ideal scheme of a possibly sampling-based sensitivity analysis

Assessing a process performance on different scales offers an effective way to refine the analysis and improve the process. Results from the simultaneous application of a multiple set of methods yield consistent and comparable performance indicators and call for a two-fold optimization pattern:

(a) Upstream: trying to decrease the use of or replace those input flows which affect the material, energy and environmental support demands more heavily;

(b) Downstream: trying to decrease the use or avoid misuse of the investigated product, in order to negatively affect the input demand by controlling the end of the life cycle chain.

The ultimate goal of any investigation about a process is to generate a clear picture of the crucial steps as well as crucial input and output flows, i.e. those steps and those flows that affect more heavily the process performance. In so doing it is possible to focus on these steps and flows, to understand how important they are in the global economy of the investigate process, and to suggest changes capable of leading to an improved performance. Some steps may be replaced by alternative patterns, some flows may be decreased by means of more efficient machinery or sub-processes, and finally some flows may simply be avoided without any important consequence for the final product. Suggesting an optimization procedure is not an easy task. Indicators are the result of a calculation procedure where the inventory data are multiplied by intensity factors specific of each given method (e.g. oil equivalent factors, transformity, global warming potential, etc.). Therefore, when a performance indicator (e.g., the Acidification Potential) is not satisfactory, the analyst goes back to the calculation procedure in order to identify the input items that are responsible forthe largest contributions to that impact category and may suggest decreasing their amount by applying technological changes to the process (e.g., use of de-sulphurized fuel). After the suggested changes have been implemented (or their adoption has been simulated) in the process, the analyst will recalculate the indicator under consideration and will assess the extent of the performance improvement. However, it is very likely that the suggested change affects other impact categories and, due to the reliance on the same set of input data, the improvement in one category might translate into a worse performance in another category (e.g. fuel de-sulphurization requires an additional technological process and increased energy input and generates additional waste to dispose of).

3. Methods

Sensitivity Analysis applied to the emergy approach is showed in the following section in order to explain the procedure and the obtained results for the selected case study of Beijing metabolic system in the year 2006. The same procedure can be applied to every emergy evaluations for different years and different scales.

Since emergy analysis is based on a single common inventory of all the system's inputs and outputs, a systematic sensitivity analysis has been simultaneously performed on all calculated data and indicators, simply by allowing for variable cells for all input quantities as well as for the associated impact coefficients (intensity factors) in the spreadsheet-based calculation procedures. Such an analysis is invaluable in order to estimate the actual reliability of the impact assessment itself, accounting for the inevitable uncertainties and variability in the input data and/or intensity factors, as well as singling out the most critical key points of the analyzed process in the light of the different assessment methods. The main goal of emergy analysis approach is to provide suggestions to governance (policy makers, local institutions) in order to optimize the dynamics of the investigated systems (optimization procedure). Here, Excel's Data Table is chosen to command to perform sensitivity analysis for ranges of values of a model input, not just specific points (see Figure 2).

(1) enter a list of input values in a column, e.g., change radio in following table;

(2) enter a reference to an output formula at top of adjacent column;

(3) select entire table (two columns including formula).

#	Items	Units	Raw amount	Change radio	Test amount	Transformity (seJ/unit)	Emergy (seJ/yr)
put (locally available)							
1	Sun	J/yr	7.02E+19	0.00%	7.02E+19	1	7.02E+19
2	Wind (Kinetic Energy of Wind Used at the Surface	J/yr	4.87E+16	0.00%	4.87E+16	2.51E+03	1.22E+20
3	Rainfall (Geopotential Energy)	J/yr	1.25E+15	0.00%	1.25E+15	1.74E+04	2.19E+19
4	Rainfall (Chemical Potential)	J/yr	1.12E+16	0.00%	1.12E+16	3.05E+04	3.43E+20
5	Geothermal Heat	J/yr	1.79E+16	0.00%	1.79E+16	5.76E+04	1.03E+21
6	Hydroelectricity	J/yr	2.30E+14	0.00%	2.30E+14	3.36E+05	7.74E+19
7	Stream flow	J/yr	8.81E+15	0.00%	8.81E+15	3.05E+04	2.69E+20
8	Top soil (erosion, wheathering)	J/yr	3.17E+14	0.00%	3.17E+14	1.23E+05	3.90E+19
9	Fuels input from locol region						
	Coal=	J/yr	2.04E+17	0.00%	2.04E+17	6.69E+04	1.37E+22
	Oil=	J/yr	0.00E+00	0.00%	0.00E+00	9.08E+04	0.00E+00
	Natural gas=	J/yr	0.00E+00	0.00%	0.00E+00	9.85E+04	0.00E+00
10	Constructed local input						
	Limestone=	g/yr	1.52E+13	0.00%	1.52E+13	1.68E+09	2.55E+22
	Sand and gravel=	g/yr	1.02E+13	0.00%	1.02E+13	1.68E+09	1.70E+22
	Iron ore=	g/yr	1.68E+13	0.00%	1.68E+13	1.44E+09	2.41E+22
11	Fuels import						
	Crude coal (from other provices)=	J/yr	6.17E+17	10.00%	5.55E+17	6.69E+04	3.71E+22
	Washing Coal(from other provices)=	J/yr	8.53E+16	0.00%	8.53E+16	8.02E+04	6.85E+21
	Washing Coal(from other countries)=	J/yr	0.00E+00	0.00%	0.00E+00	8.02E+04	0.00E+00
	Other washing coal (from other provices)=	J/yr	2.15E+15	0.00%	2.15E+15	8.02E+04	1.73E+20
	moulded coal(from other provices)=	J/yr	3.85E+15	0.00%	3.85E+15	1.10E+05	4.22E+20
	Cok e(from other provice)=	J/yr	4.72E+16	0.00%	4.72E+16	1.10E+05	5.18E+21
	crude oil (from other provices)=	J/yr	2.66E+17	0.00%	2.66E+17	9.08E+04	2.41E+22
	crude oil (from other countries)=	J/yr	7.91E+16	0.00%	7.91E+16	9.08E+04	7.19E+21
	Gasoline (from other provices)=	J/yr	9.20E+16	0.00%	9.20E+16	1.05E+05	9.64E+21
	Kerosene (from other provices)=	J/yr	5.24E+16	0.00%	5.24E+16	1.10E+05	5.77E+21
	Kerosene (from other countries)=	J/yr	7.08E+16	0.00%	7.08E+16	1.10E+05	7.79E+21
	Diesel Oil (from other provices)=	J/yr	8.61E+16	0.00%	8.61E+16	1.10E+05	9.48E+21
	Fuel Oil (from other provices)=	J/yr	4.42E+15	0.00%	4.42E+15	1.10E+05	4.87E+20
	Fuel Oil (from other countries)=	J/yr	0.00E+00	0.00%	0.00E+00	1.10E+05	0.00E+00
	liquefied petroleum gas (LPG)=	J/yr	6.66E+15	0.00%	6.66E+15	1.11E+05	7.37E+20
	Natural gas(from other provices)=	J/yr	1.58E+17	0.00%	1.58E+17	9.85E+04	1.56E+22

Fig. 2 Sample of Excel's Data Table

Next, results are organized in Tables where different impact indicators are listed in relation to different scenarios.

Table 1 Example of table of calculated indicators.

#	RAW DATA			
	Dataset 1	Dataset 2	Dataset 3	Dataset 4
Indicator 1	A_1	B_1	C_1	D_1
Indicator 2	A_2	B_2	C_2	D_2
Indicator …	$A_{...}$	$B_{...}$	$C_{...}$	$D_{...}$
Indicator n-1	A_{n-1}	B_{n-1}	C_{n-1}	D_{n-1}
Indicator n	A_n	B_n	C_n	D_n

4. Results

Sensitivity Analysis was applied to different dataset to point out the system behavior in relation to different scenarios. As pointed out previously, our results were obtained by implementing a calculation procedure on an excel platform. This also allowed us to perform a sensitivity analysis, by gradually assuming a variation of the main inflows by ±10%, ±20%, …, ±50%, and assessing to what extent such a variation affected the final results (i.e., the environmental sustainability index, CO_2 emission, globe to local CO_2 ratio, et al.). The variation can be independently applied to the raw amount of each input flow, in so accounting for the uncertainty of estimates and possible errors. We applied the procedure to selected individual flows larger than 3% of total emergy use (imported coal, imported oil, imported natural gas, imported electricity, etc.).

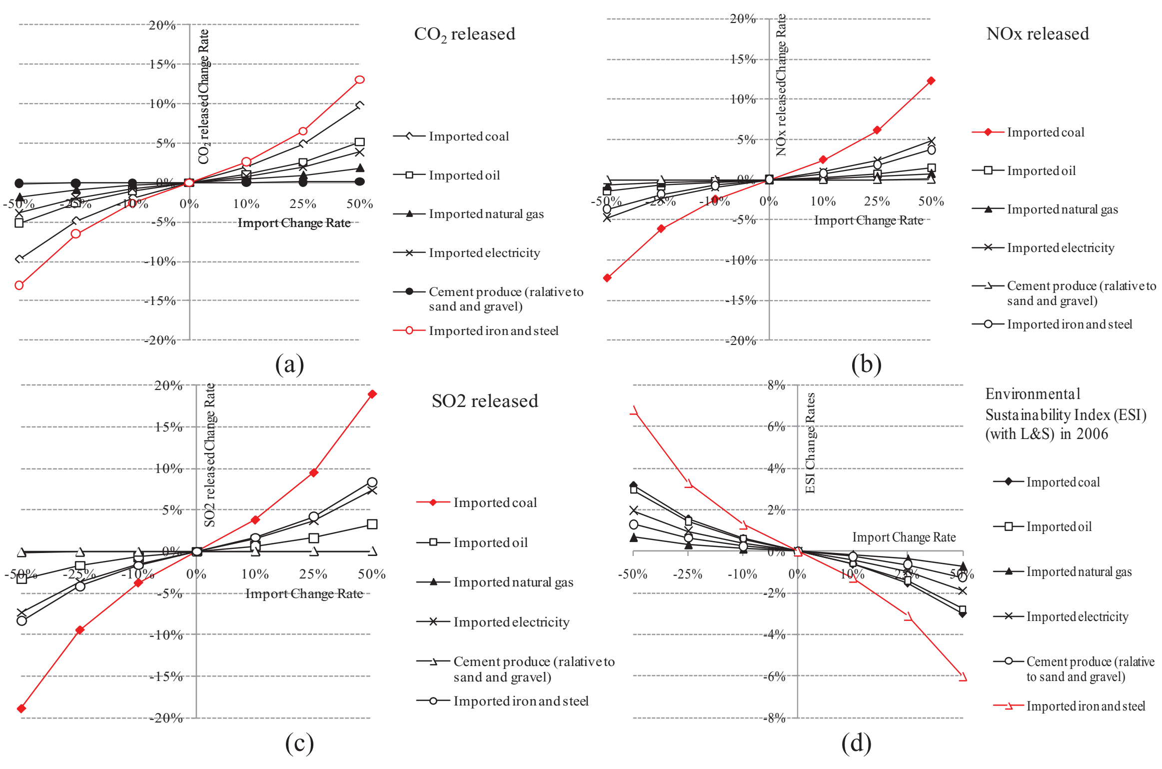

Fig. 2 Sensitivity analysis between import change rate and different emissions (a. CO_2; b. NO_x; c. SO_2) and d. ESI change rate

We performed three sensitivity analysis results on the 6 imported parameters. This allowed us to fix those whose effects on the observed variables were negligible. Based on these observations, we obtain the following conclusions:

(1) The parameter of imported iron and steel has most significant efforts for all the change rates, as in the configuration examined previously. It was the direct result from rapid construction appealed by national and local government in Beijing.

(2) The effects of imported fuels are significant for the change rates of ESI and CO_2 emissions. But they exhibit the opposite behavior to global to local CO_2 ratio change with cement produce and imported iron and steel. That's because the fuels have the direct local emissions while the imported sand, iron and steel only have the indirect emissions.

(3) These parameters are linearly related to all the change rates.

The results show that the pressure of environmental protection which was caused by over-heated investment in Beijing could be released after finishing the infrastructure construction and curbing environmental pollution and improving environmental quality by focusing on fuel import, greenhouse gas control and air pollution treatment.

5. Conclusion

Such an "integrated system" strategy requires integration of policies and infrastructures for both agricultural and industrial sectors. Another prerequisite for its success is the preliminary increase of efficiency of each individual process and component, more appropriate use of energy, water, materials, and cost-effective application of solar energy devices such as thermal and photovoltaic modules in order to meet those energy needs that cannot be met by biomass energy or by energy conservation practices and indirect savings. Integration of production units is a pattern that can be implemented – with appropriate changes – in every city of China, in order to take advantage of specific properties and productive abilities of local systems and ecosystems.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 40871056), Major Program of National Natural Science Foundation of China (Grant No. 50939001) and National Science Foundation for Distinguished Young Scholars (Grant No. 50625926).

References

[1] Odum HT. The ecosystem, energy and human values. *Zygon* 1977;**12**:109–133.

[2] Ulgiati S, Bargigli S, Raugei M. An emergy evaluation of complexity, information and technology, towards maximum power and zero emissions. *J Cleaner Product* 2007;**15**(13–14),1354–1372.

[3] Jørgensen SE. Eco-exergy as an ecosystem health indicator. *Encycl Ecol* 2008;977–979.

[4] Ulgiati S., Brown MT. Emergy and ecosystem complexity. *Comm in Nonlinear Sci & Num Sim* 2009;**1**(14):310–321.

[5] Odum HT. Systems ecology. *New York: John Wiley and Sons*; 1983.

[6] Odum HT. Living with complexity. The Crafoord Prize in the Bioscience. Crafoord lectures. *The Royal Swedish Academy of Science*; 1987.

[7] Tilley DV, Swank WT. Emergy-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. *J Environ Manag* 2003;**69**:213–227.

[8] Pannell DJ, Wilkinson R. Policy mechanism choice for environmental management by non-commercial "lifestyle" rural landholders. *Ecol Econ* 2009;**68**(1):2679–2687.